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Resource Potential of the Southern Leyte Geothermal Prospect, Philippines: A Geologic Evaluation

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ABSTRACT

The Southern Leyte Geothermal Prospect is located at the southeastern tip of Leyte island in the Philippines. Mt. Cabalian and Mt. Cantoyocdoc comprise the Quaternary volcanoes in the area.

Surface exploration studies indicated a viable geothermal resource possibly centered beneath Mt. Cabalian. In 1997, the first exploration well SL-1D was drilled on the eastern flanks of Mt. Cabalian. However, it was non-productive due to poor permeability, and measured low temperatures of only ~240°C at –1870 m MSL. To better define the configuration of the deep geothermal reservoir, a more detailed magnetotelluric (MT) survey was conducted in 2000. In contrast to the pre-drilling model, results of MT surveys point to an upflow centered near the western flanks of Mt. Cantoyocdoc. Hence, in 2003, the second exploration well SL-2D was drilled towards this direction. Well SL-2D encountered better permeability and higher temperatures in comparison to the non-productive well SL-1D. Based on fluid inclusion and alteration mineralogy (*i.e.*, garnet, actinolite, euhedral epidote), well SL-2D will produce hot neutral brine with temperature of ~280°C at –1840 m MSL.

Results of exploration drilling and MT surveys showed that an active geothermal system exists in Southern Leyte whose hottest part is likely centered near the western flanks of Mt. Cantoyocdoc. Transport of fluids across the reservoir is achieved through permeable faults and stratigraphic contacts. Major fluid outflows gave rise to surface thermal manifestations mapped east and west of the field. Based on MT anomaly, the size of the potential geothermal resource in Southern Leyte is ~7.5 to 12 km^2. To target center of this resource, the next wells should be drilled from a new pad located north of well SL-2D. From the existing pad of well SL-2D, another well may be drilled towards the northwest to delineate southern boundary of the geothermal resource.

1. INTRODUCTION

The Southern Leyte Geothermal Prospect (SLGP) is located at the southeastern tip of Leyte Island in the Philippines (Fig. 1). Mts. Cabalian and Cantoyocdoc comprise the Quaternary stratovolcanoes in the area. These two stratovolcanoes form part of the eastern Philippine volcanic front (Datuin, 1982) which runs from Camarines Norte down to Davao del Norte, and is aligned sub-parallel to the Philippine Trench and the Philippine Fault. In Leyte island, the 723-MWe Leyte Geothermal Production Field (LGPF) lies along the northern portion of this volcanic front, while the SLGP is situated in the southernmost part (Fig. 1).

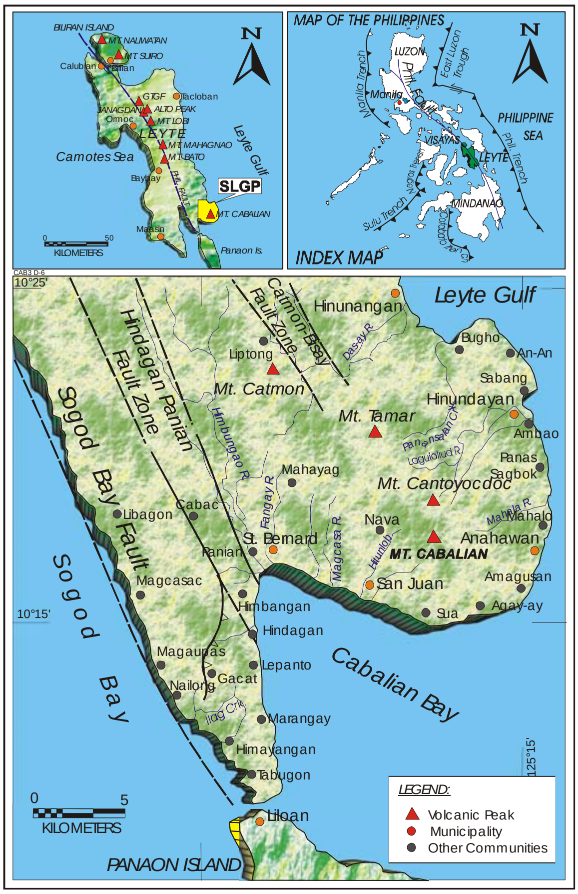

Figure 1: Location map of Southern Leyte geothermal prospect

This paper will discuss results of surface exploration and drilling activities conducted in the area. A geologic model of the SLGP geothermal system will be presented based on these exploration studies.

2. EXPLORATION ACTIVITIES

2.1 Surface Exploration

Initial surface exploration studies were done in Mt. Cabalian area by Bureau of Energy Development (BED) and Electroconsult of Italy (ELC) in 1979. An inventory of thermal springs yielded an estimated reservoir temperature of 221°C based on chemical geothermometry (BED-ELC, 1979).

PNOC-EDC started reconnaissance geoscientific surveys in SLGP in early 1980's. Favorable results of these investigations led to a detailed geoscientific investigation undertaken by PNOC-EDC in 1989. This included geologic mapping (1:50,000 scale), geochemical sampling and analyses of thermal waters and gases, and

Schlumberger Resistivity Traversing (SRT) and Vertical Electrical Sounding (VES) surveys (PNOC-EDC, 1989).

Results of these surveys indicated an upflow of hot, neutral-chloride fluids (minimum temperatures of 190-205°C) associated with Late Pleistocene summit eruptions of Mt. Cabalian. Two low-resistivity anomalies defined the major fluid outflows to the east emerging as Mahalo-Mainit thermal springs, and to the west towards Nava and Tabunan springs (Fig. 2). To test this model, two exploration wells were recommended, one targeting the postulated upflow zone beneath Hugpa crater (Site A), and another intersecting major fluid outflow towards Mainit-Mahalo sector (Site B).

In preparation for exploration drilling scheduled in 1997, PNOC-EDC conducted additional geoscientific surveys in September 1996 starting with detailed microtectonic and structural mapping with repeat geochemical and isotopic sampling. Regional gravity and magneto-telluric surveys (MT) were also conducted to characterize the subsurface geometry of the geothermal reservoir in Mt. Cabalian. These studies further strengthened the exploration model of an active geothermal system related to intrusive bodies beneath Mts. Cabalian and Cantoyocdoc (Fig. 3). In addition to the two drilling sites, a third (Site C) was recommended to target the northeastern sector of the geothermal resource (Leynes *et al*., 1996).

2.2 Exploration Drilling

In September 1997, the first exploration well in Southern Leyte (SL-1D) was drilled from Site B on the eastern flanks of Mt. Cabalian (Fig. 4). Well SL-1D was deviated towards the northwest to intersect deep outflowing fluids towards the eastern portion of the postulated geothermal resource. Table 1 shows the basic well data of SL-1D which reached a total vertical depth (VD) of 2398 m.

Table 1: Basic well data of SL-1D and SL-2D

	Well SL-1D	Well SL-2D
Elevation	526 m	517 m
Pad	Site B	Site C
Throw azimuth	337°	360°
Kick-off point	214 m	842 m
Total vertical depth	2398 m	2362 m
Total throw	1178 m	624 m
Surface Casing	152 m	100 m
Anchor Casing	758 m	768 m
Production Casing	1722 m VD	1543 m VD
Total Days Drilled	74	68

Well SL-1D failed to intersect any permeable structure below its production casing shoe (~1720 m VD) based on its low injectivity index, and absence of drilling losses and drusy veins throughout its length (Rosell and Zaide-Delfin, 1997). In addition, the well only reached a maximum measured temperature of ~240°C at its bottom (–1870 m MSL) which correlates with alteration mineralogy. No attempt was made to discharge the well because of its low temperature and tight permeability.

Due to unsuccessful results of well SL-1D, additional studies were undertaken in Southern Leyte to better define the configuration of the geothermal reservoir. These studies include a more detailed magneto-telluric survey in 2000. Results of this survey indicated that center of the geothermal resource possibly lies at the western flanks of Mt. Cantoyocdoc (Fig. 5), and not beneath Mt. Cabalian as postulated in the pre-drilling model (Rigor *et al*., 2001). The proposed center of the resource also coincided with a high-gravity anomaly interpreted to be a large intrusive body beneath the two Quaternary volcanoes Cabalian and Cantoyocdoc (Catane and Apuada, 1998).

The second exploration well SL-2D was drilled in 2003 to test the revised MT model. It was spudded on Site C (Fig. 4) on the western side of Mt. Cabalian, and targetted towards the western flanks of Mt. Cantoyocdoc. The well reached a total vertical depth of 2362 m (Table 1).

Well SL-2D encountered hotter temperatures and better permeability in comparison to the first well SL-1D (Zaide-Delfin *et al*., 2003). Drilling losses and abundant drusy veins attest to the good permeability of faults intersected by SL-2D; while alteration mineralogy indicates ~280°C neutral-pH fluids near bottom hole at -1840 m MSL. Results of well SL-2D therefore confirmed that the hot region in SLGP lies near the western flanks of Mt. Cantoyocdoc, and not beneath Mt. Cabalian as previously postulated.

3. STRATIGRAPHY AND PERMEABILITY

3.1 Reservoir Rocks

The two deep exploration wells in Southern Leyte were both spudded on Late Pleistocene eruptives of Mt. Cabalian which belong to the stratigraphic unit termed as Quaternary Volcanics (QV) (Leynes *et al*., 1996). The QV is ~660 meters thick in well SL-1D, but reaches ~1085 meters in well SL-2D (Fig. 6). It can be further subdivided into an upper and a lower member (Table 2). The upper member is composed of oxyhornblende clinopyroxene andesite lavas and tuff breccias. The lower member, on the other hand, consists of dacitic to andesitic lavas and tuff breccias with minor clasts of basalts and sedimentary rocks.

Separated by an unconformity, the QV is underlain by Middle Miocene limestones and clastic rocks belonging to the Tertiary Clastics (TC). Both wells were terminated within the TC that reached a thickness of ~1740 meters in SL-1D and ~1280 meters in SL-2D (Fig. 6). The TC is made up of a thick sequence of fossiliferous limestone, calcareous sandstone and breccia with lesser amounts of carbonaceous siltstone and claystone.

Based on surface geologic mapping, the TC is expected to be underlain by a thinner sedimentary sequence of Early-Middle Miocene age termed as Tertiary Limestones (TL). Below the TL is the oldest formation mapped in the area, the Cretaceous Ultramafics (CU) that forms the basement rock of Southern Leyte (Leynes *et al*., 1996).

In both wells, the Tertiary Clastics was intruded by several dike bodies (Fig. 6). In SL-2D, hornblende dacite dikes cut the TC at 1130-1200 m, 1260-1540 m, and 2240-2350 m; while a pyroxene hornblende microdiorite dike cut the TC from 1580 m down to 2100 m. On the other hand, a hornblende dacite dike intruded the TC in SL-1D at 1640-1860 m. Intrusions of these dike bodies resulted to thermal metamorphism of TC limestones and clastic rocks producing a hornfelsic mosaic of garnet + pyroxene + vesuvianite.

3.2 Reservoir Permeability

The Southern Leyte area is transected by numerous northeast and northwest trending faults that control the distribution of surface thermal manifestations. Transport of fluids across the geothermal reservoir is achieved through these permeable structures based on results of well SL-2D. The main permeable zone in SL-2D at 1740-1920 m coincides with the intercept of Imburna Splay, a major northwest-trending fault that cuts across the peak of Mt. Cabalian. Drusy veins and drilling losses further attest to the good permeability of Imburna Splay. Near bottom of SL-2D, well completion tests delineated a second permeable zone at 2250-2360 m correlative with Tagbikay Fault, a northeast-trending structure that runs across the summit of Mt. Cantoyocdoc.

In well SL-1D sector however, faults are found to be permeable only at shallow levels of the reservoir. The most permeable portion of SL-1D occurs at ~700 m which lies above the production casing shoe (PCS). This permeable section is attributed to the intercept of Mahalo Fault Splay and is characterized by massive drilling losses and abundant drusy veins. Below the PCS however, no more permeable faults were encountered by SL-1D. The targeted intersections of Mahalo Fault at 1780-2050 m and Kaguingkingan Fault at 2250-2390 m are both tight as indicated by absence of drilling losses and drusy veins. The low injectivity index of SL-1D further confirmed the impermeability of these structures at deep levels in this sector of the field.

Aside from faults, stratigraphic and intrusive contacts also provide permeable channels for reservoir fluids in Southern Leyte. In both SL-1D and SL-2D, drusy vein minerals are found along the unconformable contact between Quaternary Volcanics and Tertiary Clastics; and in SL-2D, drilling losses occurred along the contact. Dike intrusions likewise contribute to reservoir permeability as indicated by their correspondence with permeable zones and drilling losses.

4. HYDROTHERMAL ALTERATION

The rock units encountered by wells SL-1D and SL-2D show moderate to intense alteration by hot, neutral-pH fluids. Alteration minerals produced by acid fluids were not observed in both wells. The onset of hydrothermal alteration lies at –260 m MSL affecting TC sedimentary units in SL-1D, and QV lower member in SL-2D. The QV upper member remains fresh to slightly weathered.

With increasing depth, hydrothermal alteration in both wells show a progradational trend from low to higher ranks of alteration assemblage (Table 3). The low-rank type of hydrothermal alteration is characterized by the assemblage of quartz, illite-smectite and incipient to anhedral epidote. Based on stable measured temperatures in both wells, this alteration assemblage occurs at ~180-200°C. In well SL-1D, low-rank type of alteration replaced TC sedimentary units from –260 m down to –1000 m MSL. On the other hand, low-rank alteration minerals are observed within the QV lower member in well SL-2D at –260 m down to –600 m MSL.

Medium-rank hydrothermal alteration occurs within the Tertiary Clastics in both wells SL-1D and SL-2D. Its mineral suite consists of anhedral to subhedral epidote, the clays illite and illite-smectite, and the zeolites wairakite and laumontite. Stable measured temperatures showed that medium-rank alteration occurs at ~200-240°C. In well SL-2D, this alteration rank exists from –600 m down to –950 m MSL; while in well SL-1D, it was observed at –1000 m MSL and extended down to bottom of the well at –1870 m MSL where the maximum measured temperature is only ~240°C.

High-rank type of hydrothermal alteration formed only in well SL-2D within the Tertiary Clastics starting at –950 m MSL down to well bottom (-1840 m MSL). The typical alteration assemblage is composed of euhedral epidote, actinolite and garnet which is stable at ~240-280°C based on their known occurrences in Philippine geothermal fields. Within the high-rank alteration zone, fluid inclusions in veins of calcite, anhydrite and quartz gave homogenization temperatures (T_h) ranging from ~250°C to ~280°C (Zaide-Delfin *et al*., 2003). At deeper levels in well SL-2D, measured temperatures are not yet stable due to drilling fluids still present inside the bore. Thus, the maximum measured temperature of ~209°C (KT-8, 20 day shut) at –1840 m MSL is expected to increase to ~280°C once the well has been fully discharged.

Results of exploration drilling therefore showed that hotter temperatures exist west of Mt. Cantoyocdoc where SL-2D was targeted in comparison to the sector east of Mt. Cabalian where SL-1D was drilled. In SL-2D, neutral-pH fluids with temperatures of ~280° are likely flowing at –1840 m MSL based on fluid inclusion studies and presence of high-rank alteration. At –1870 m MSL in SL-1D, on the other hand, maximum measured temperature is only ~240°C correlative with medium-rank alteration.

5. GEOLOGIC MODEL OF THE GEOTHERMAL SYSTEM

An active geothermal system exists in Southern Leyte whose hottest portion is likely centered near the western flanks of Mt. Cantoyocdoc as delineated by magnetotelluric surveys and confirmed by exploration drilling. The heat source which likely drives the geothermal system can be associated with Late Pleistocene volcanism which gave rise to Mts. Cantoyocdoc and Mt. Cabalian. Radiometric and thermoluminescence dating confirmed the Late Pleistocene age of both Mt. Cabalian and Mt. Cantoyocdoc (Leynes *et al*., 1996; Ramos *et al*., 1998). Dacite and microdiorite dikes intruding the Tertiary Clastics were likely derived from the same magmatic chamber that erupted these two volcanoes.

Within the upflow region, hot, neutral-pH fluids are likely channeled vertically along permeable faults mapped west of Mt. Cantoyocdoc such as Hitunlob and Gahong faults (Fig. 4). Hot fluids may also ascend along permeable contacts of dike bodies intruding reservoir rocks. Based on results of well SL-2D, temperature of upflowing fluids in Southern Leyte reach ~280°C at –1840 m MSL (Fig. 7).

From the upflow sector, hot fluids migrate horizontally along faults, and across the stratigraphic contact between QV and TC. Based on resistivity surveys and distribution of thermal manifestations, hot fluids outflow along two major directions. The eastward outflow sector drilled by well SL-1D produced the Mahalo-Mainit thermal areas; while fluid outflows to the west gave rise to the Nava and Tabunan thermal springs.

The depth of fluid outflows lies above –1000 m MSL based on results of SL-1D. Faults within the outflow sectors are impermeable at deep reservoir levels below –1200 m MSL. In fact, the most permeable portion of well SL-1D occur at shallow reservoir levels corresponding to the intercept of Mahalo Fault Splay at –300 m MSL where ~180°C fluids are presently flowing (Fig. 7).

6. CONCLUSIONS

Based on the resistivity anomaly defined by MT surveys, the size of the potential geothermal resource in Southern Leyte is ~7.5 to 12 km^2. Well SL-2D was drilled within the southern portion of the MT anomaly; while well SL-1D already lies outside of it. To target the center of this upflow region located west of Mt. Cantoyocdoc, a new drilling pad needs to be constructed further north of well SL-2D bottom. From this new pad, the next exploration well should be directed towards the northwest to intersect structures that likely channel upwelling fluids such as Hitunlob and Gahong faults. Another exploration well may be drilled from the existing pad of SL-2D targeted to the northwest to delineate the southern boundary of the geothermal resource.

No more exploration drilling should be done from well SL-1D pad at the eastern flanks of Mt. Cabalian where temperatures are low and permeability is poor at deep reservoir levels. Likewise, no more drilling is recommended in site A near Hugpa crater because it already lies outside of the postulated geothermal resource.

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REFERENCES

Bureau of Energy Development-Electroconsult (BED-ELC). 1979. Inventory of the thermal areas in the Philippines. Philippine-Italian Technical Cooperation on Geothermics Stage II, Annex-I, 50 pp.

Catane, J.P.L. and Apuada, N.A. 1998. Structure and geothermal potential of Mt. Cabalian, Southern Leyte, Philippines based from gravity and magnetotelluric data. Geothermal Resources Council Transactions, vol. 22, pp. 265-269.

Datuin, R.T. 1982. An insight on Quaternary volcanoes and volcanic rocks of the Philippines. Journal of the Geological Society of the Philippines, vol. 36, no. 1, pp. 1-11.

Leynes, R.D., Camit, G.R.A., and Villarosa, H.A. 1996. The geology of the Southern Leyte Geothermal Project. PNOC-EDC internal report, 60 pp.

PNOC-EDC. 1989. Geoscientific exploration and evaluation of the Mt. Cabalian Geothermal Prospect, Southern Leyte. PNOC-EDC internal report, 106 pp.

Ramos, S.G., Zaide-Delfin, M.C., and Hayashi, M. 1998. Stratigraphic correlation in the Mt. Labo, Mt. Canlaon and Mt. Cabalian geothermal areas using fission-track, thermoluminescence and zircon morphology. Geothermal Resources Council Transactions, vol. 22, pp. 465-469.

Rigor, D.M., Catane, J.P.L., and Layugan, D.B. 2001. Imaging the Southern Leyte Geothermal System using MT data. PNOC-EDC internal report.

Rosell, J.B. and Zaide-Delfin, M.C. 1997. A preliminary summary of Well SL-1D petrology. PNOC-EDC internal report.

Zaide-Delfin, M.C., Catane, J.P.L., Bien, O.C., and Rosell, J.B. 2003. Geology and petrology of SL-2D, Southern Leyte Geothermal Project. PNOC-EDC internal report.

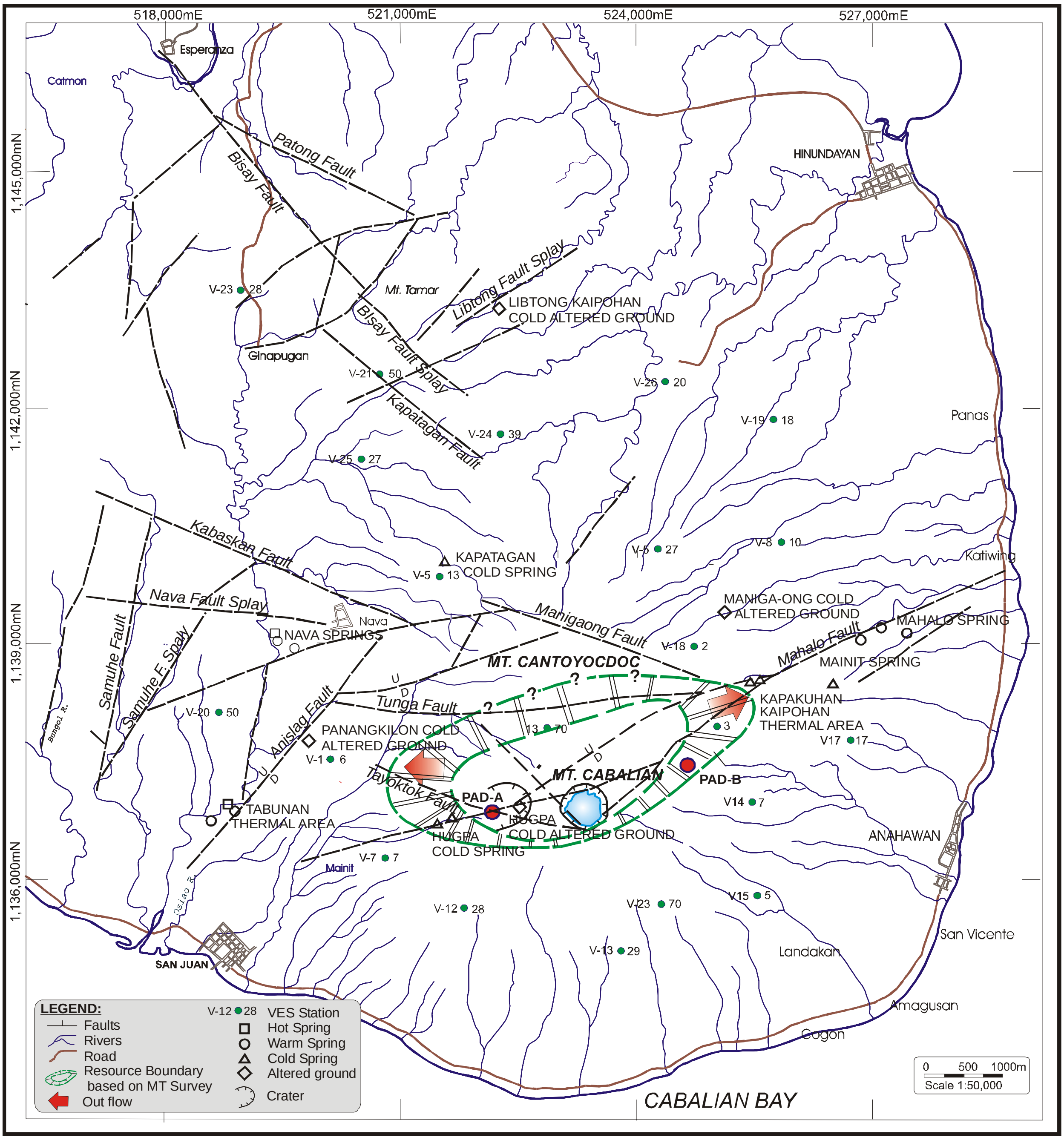

Figure 2: Pre-drilling reservoir model of Southern Leyte geothermal prospect showing interpreted resource boundary (PNOC-EDC, 1989)

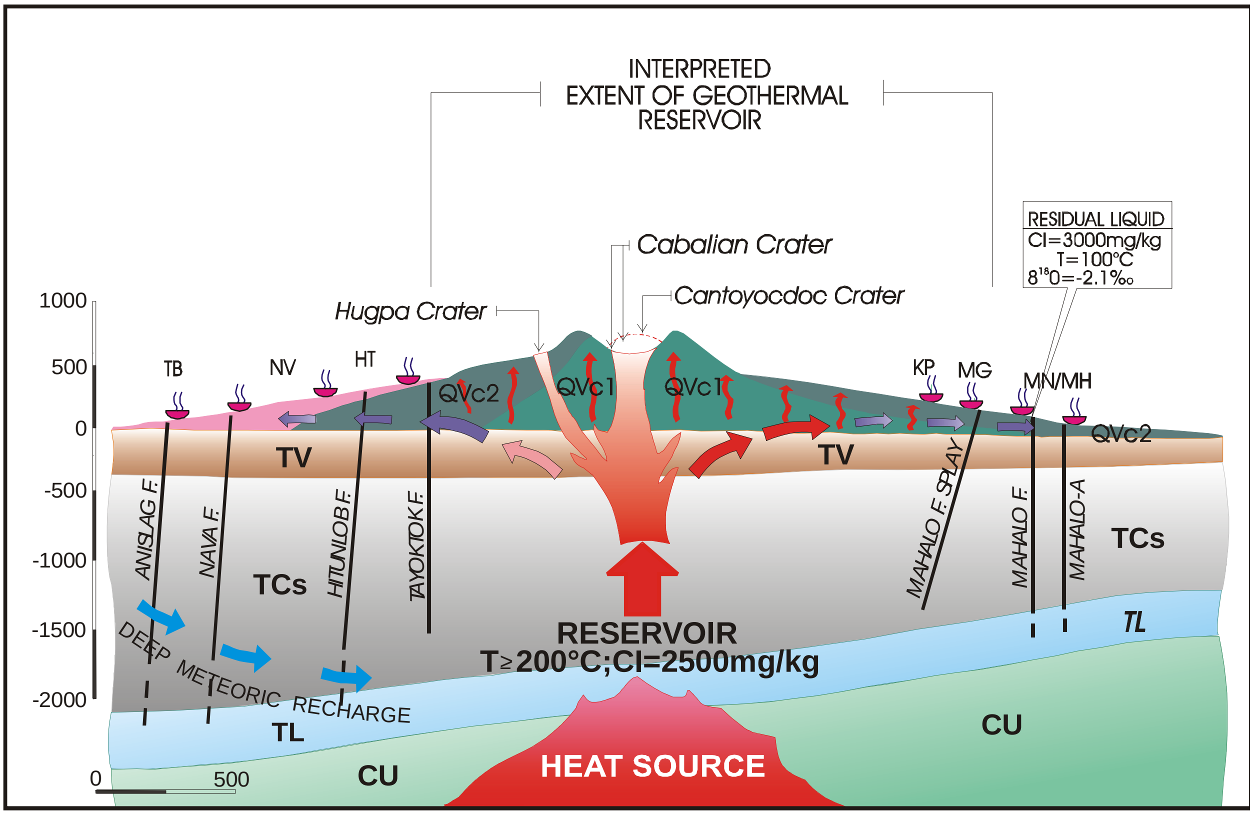

Figure 3: Integrated exploration model of Southern Leyte geothermal prospect (Leynes *et al.*, 1996)

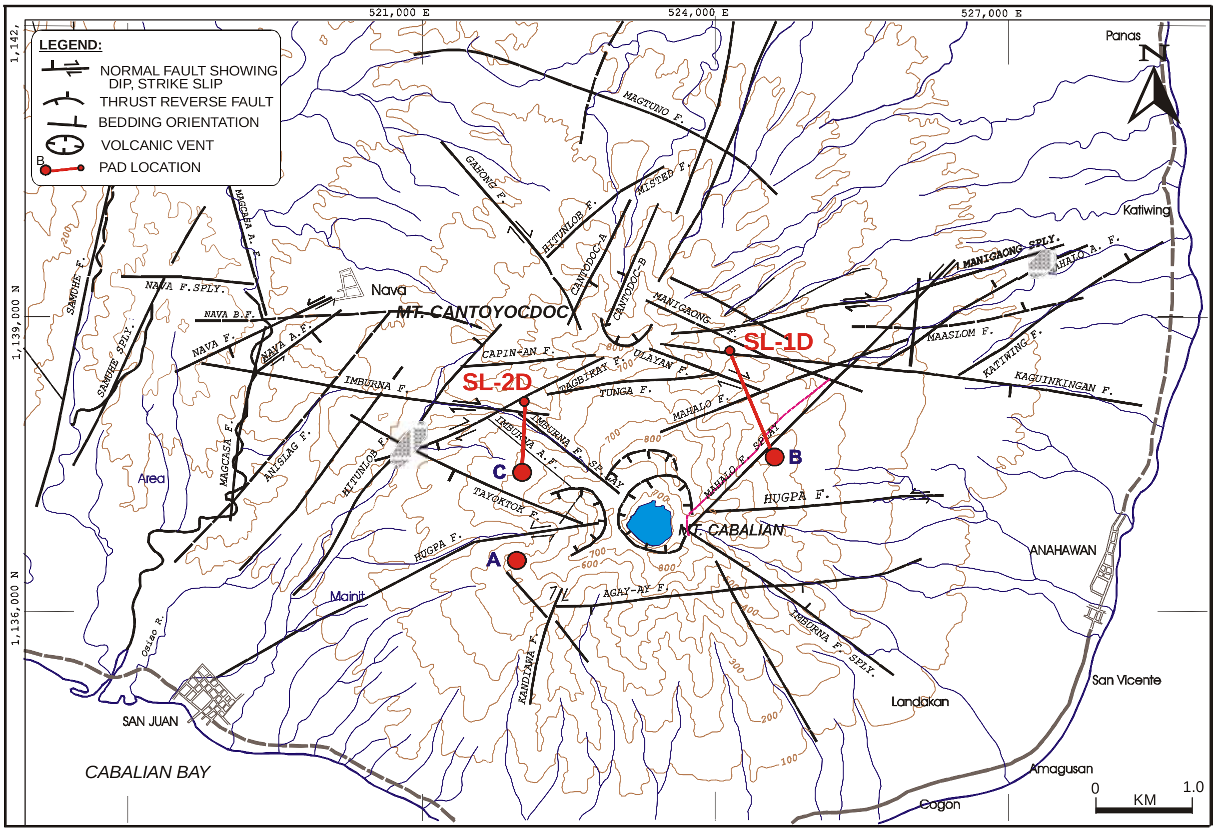

Figure 4: Structural map and location of wells SL-1D and SL-2D

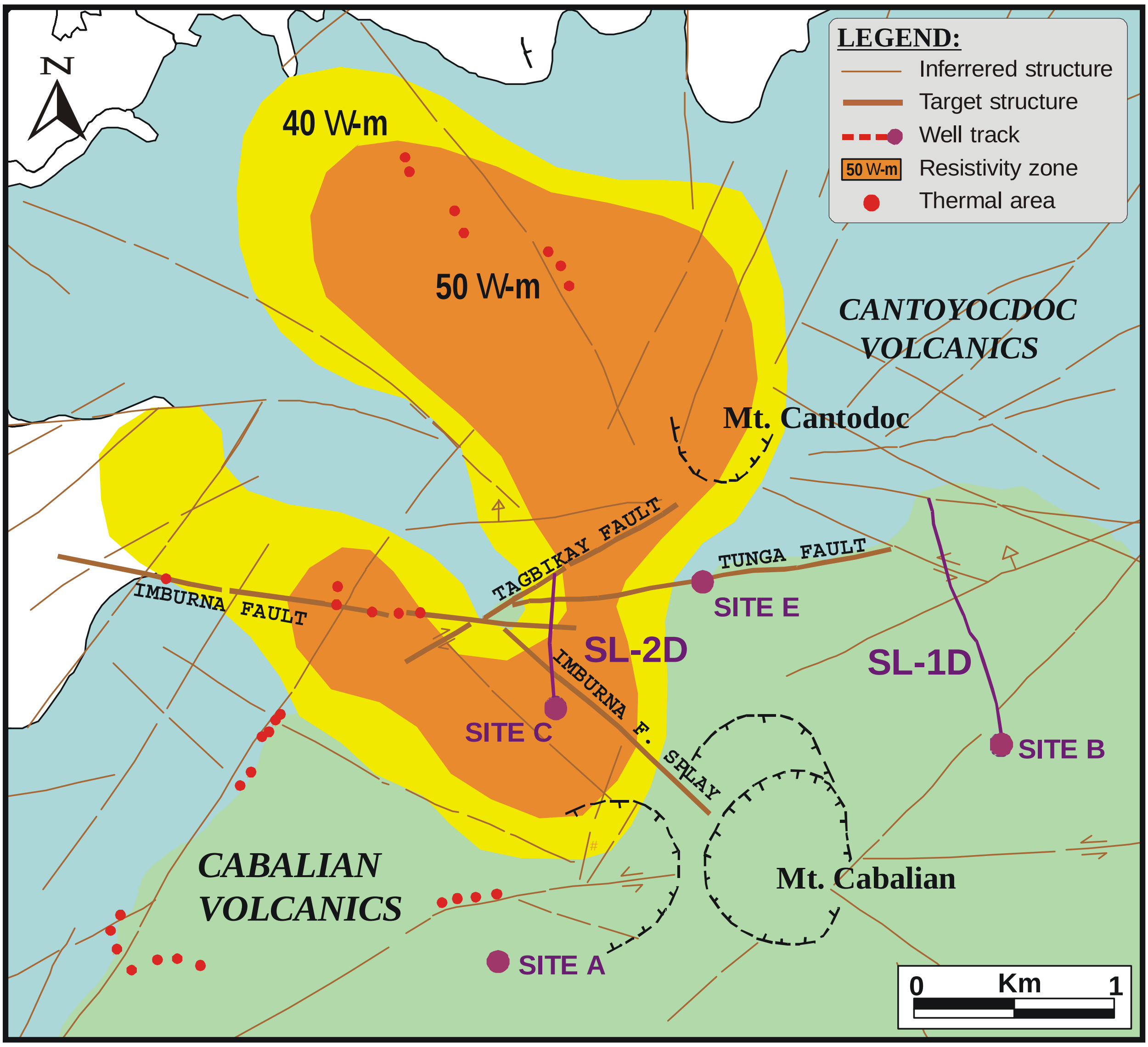

Figure 5: Geophysical model of Southern Leyte geothermal prospect showing high-resistivity region (Rigor *et al.*, 2001)

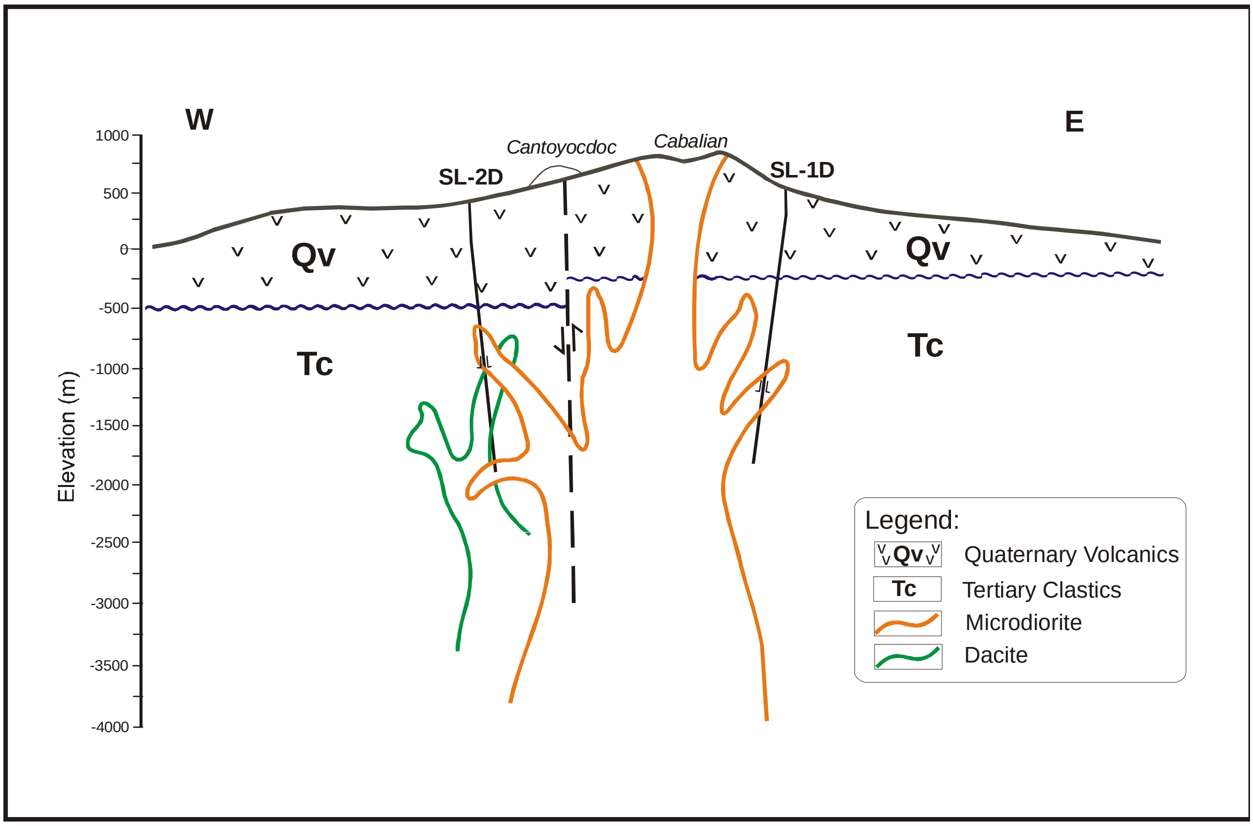

Figure 6: Subsurface stratigraphy of Southern Leyte geothermal prospect

Table 2: Stratigraphy of wells SL-1D and SL-2D

Formation	Lithology	Depth (m VD / m MSL)	
		Well SL-1D	Well SL-2D
Quaternary Volcanics (QV) Upper Member	Oxyhornblende clinopyroxene andesite lavas and tuff breccias	0-260 / +526 to +266	0-550 / +517 to –33
Quaternary Volcanics (QV) Lower Member	Dacite and andesite lavas and tuff breccias with minor clasts of basalt and sedimentary rocks	260-660 / +266 to -134	550-1085 / -33 to –568
Tertiary Clastics (TC)	Fossiliferous limestone, breccia, sandstone, siltstone and claystone	660-2398(TD) / -134 to -1872	1085-2362(TD) / -568 to –1845

Table 3: Alteration rank and assemblage in wells SL-1D and SL-2D

Alteration rank	Alteration assemblage	Temperature of occurrence (°C)	Depth of occurrence (m MSL)	
			Well SL-1D	Well SL-2D
LOW	Quartz, illite-smectite, incipient to anhedral epidote	~180-200	-260 to -1000	-260 to -600
MEDIUM	Illite, illite-smectite, anhedral to subhedral epidote, laumontite, wairakite	~200-240	-1000 to -1870 (TD)	-600 to -950
HIGH	Euhedral epidote, actinolite, garnet	~240-280		-950 to -1840 (TD)

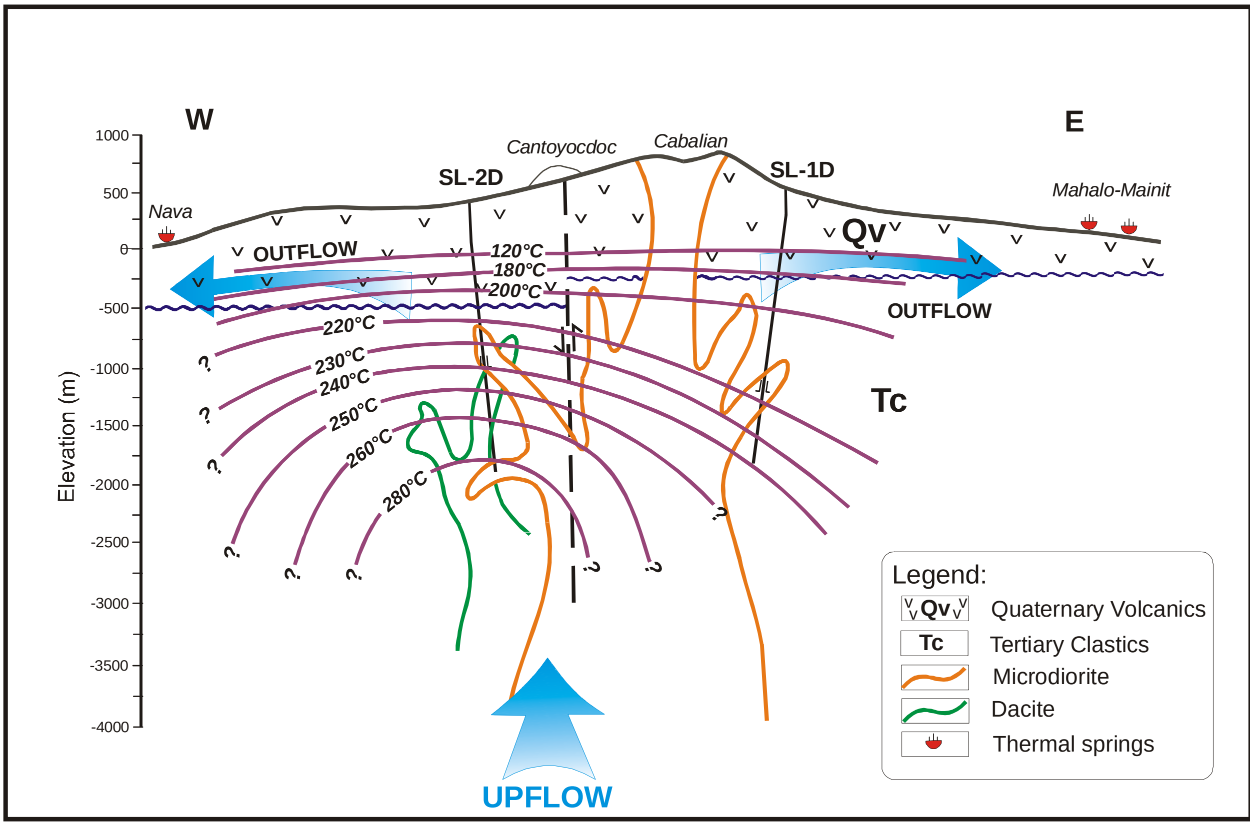

Figure 7: Geologic model of the Southern Leyte geothermal prospect (Isotherms are stable measured temperatures except below -1000 m in SL-2D which are based on alteration mineralogy)